Int. j. adv. multidisc. res. stud. 2025; 5(4):592-598

Received: 01-06-2025
Accepted: 11-07-2025

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

A Comprehensive Review of Lettuce Cultivation in Unconventional Systems: Pioneering Sustainable Food Production

[1] Bobuțac Veronica, [2] Adnan Arshad, [3] Dobrin Elena, [4] Drăghici Elena Maria
[1, 2, 3, 4] Bioengineering of Horticultural and Vinicultural Systems Department, Faculty of Horticulture, University of Agronomic Sciences and Veterinary Medicine of Bucharest 011464, City Bucharest, Romania

Corresponding Author: **Wasiu Eyinade**

Abstract

As global populations surge toward 9.7 billion by 2050, traditional agriculture faces mounting pressures from climate change, land degradation, and water scarcity. Lettuce (*Lactuca sativa* L.), a high-value leafy crop, is at the forefront of innovative cultivation systems designed to address these challenges. Unconventional systems-such as hydroponics, aeroponics, aquaponics, and vertical farming-offer transformative solutions to enhance yield, resource efficiency, and food security. This review investigates the current global status of lettuce cultivation in these systems, emphasizing their potential to revolutionize urban agriculture and sustainable food production. Literature was sourced from peer-reviewed journals (e.g., PubMed, ScienceDirect, MDPI), conference proceedings, and institutional reports published between 2018 and 2025, using keywords like "lettuce," "unconventional cultivation," and "controlled-environment agriculture." A systematic analysis of 87 studies revealed that hydroponics and vertical farming significantly outperform traditional soil-based methods, yielding up to 6.88 kg m^{-2} in controlled environments. Key parameters, including nutrient delivery, lighting, and environmental control, were correlated with growth outcomes, highlighting the synergy between technology and biology. These systems reduce water usage by up to 90% and eliminate soil-borne diseases, making them critical in water-scarce and urbanized regions. However, challenges like high energy costs and microbial risks in organic systems persist. This review proposes integrating AI-driven monitoring and renewable energy to optimize these systems, suggesting future research into cultivar-specific responses and low-cost solutions for small-scale farmers. By redefining agricultural paradigms, unconventional lettuce cultivation can play a pivotal role in ensuring global food resilience.

Keywords: Lettuce Cultivation, FAO, Romania

Introduction

Lettuce (Lactuca sativa), a globally consumed leafy vegetable, holds significant nutritional and economic value as a key component of salads, sandwiches, and wraps. With global production nearing 27 million metric tons annually (FAO, 2023) [13], its importance in human diets is underscored by its richness in vitamins A, C, K, and folate. However, the traditional model of soil-based cultivation is increasingly strained by rapid urbanization, land degradation, erratic climate conditions, and shifting dietary patterns. As arable land shrinks—declining by an estimated 0.1% annually (UNCCD, 2022) [43]-and extreme weather events intensify, conventional agriculture struggles to meet the escalating demand for fresh produce. These pressures demand a paradigm shift toward innovative, sustainable cultivation strategies.

Unconventional systems such as hydroponics, aeroponics, aquaponics, and vertical farming offer transformative alternatives by decoupling plant growth from soil and natural climate cycles (Arshad *et al*., 2024) [3]. These controlled-environment agriculture (CEA) approaches optimize inputs like water, nutrients, and light while enabling consistent, high-quality yields in otherwise non-arable spaces, including urban rooftops and desert environments (Nitu *et al*., 2025) [32]. Hydroponics alone can reduce water use by up to 90% compared to traditional soil farming (Barbosa *et al*., 2015) [5], while vertical farming multiplies land efficiency, achieving yields hundreds of times greater per square meter through vertical stacking and precise environmental management. Lettuce, with its short growth cycle and adaptability, is particularly suited to these systems, often reaching harvest in just 30–45 days under optimal conditions.

At the core of these systems lies a suite of interconnected technologies. Precision nutrient delivery through systems like nutrient film technique (NFT), deep water culture (DWC), and ebb-and-flow enables targeted root zone management, enhancing biomass accumulation and nutrient uptake. Supplementary lighting using high-efficiency LEDs tailors spectral quality and intensity to optimize photosynthesis, while environmental control systems manage temperature, humidity, CO_2, and airflow with minimal variance. Growing media-ranging from organic substrates like coconut coir and peat to inert materials like rockwool and perlite-anchor the root systems without relying on traditional soil. These variables collectively influence key growth metrics such as fresh and dry biomass, leaf area, vitamin and antioxidant content, and overall crop uniformity.

Hydroponics remains the most widely adopted system, particularly the NFT method, which provides a continuous, thin flow of nutrients over plant roots (Nitu *et al*., 2024). This technique is especially favored in lettuce cultivation for its efficiency and scalability, often yielding 20–30% more biomass than soil-based methods (Kratky, 2010) [25]. In DWC, roots are submerged in aerated nutrient solutions, supporting accelerated growth but necessitating continuous oxygenation to prevent root diseases. Aeroponics, in contrast, suspends roots in air and mists them with nutrient-rich solutions, delivering maximum oxygenation and water efficiency-using 95% less water than conventional methods (Lakhiar *et al*., 2018) [26]-and reducing growth cycles by up to two weeks. Lettuce cultivated aeroponically often reaches fresh weights of 200-300 grams per plant, with superior root health and nutrient content.

Aquaponics integrates hydroponic crop production with aquaculture, creating a symbiotic loop where fish waste provides plant nutrients, and plants help purify water for fish. Lettuce performs well in such systems due to its modest nutrient demands and tolerance to fluctuating mineral concentrations. Systems combining tilapia and lettuce cultivation report yields of 4–6 kg/m² per cycle (Rakocy *et al*., 2006) [35], with substantial reductions in external fertilizer inputs. However, aquaponics demands nuanced balancing of biological systems, water chemistry, and biofiltration to ensure optimal performance. Meanwhile, vertical farming represents the convergence of hydroponics or aeroponics with multi-tiered growing platforms, artificial lighting, and automated controls. This model can yield 50–100 kg/m² of lettuce annually (Despommier, 2010) [12], leveraging proximity to urban centers to reduce transport emissions and enhance food security. Despite their promise, vertical farms are energy-intensive, with lighting and climate regulation accounting for 30–40% of operational costs (Graamans *et al*., 2018) [18].

When compared to traditional open-field and greenhouse cultivation, unconventional systems offer pronounced advantages in efficiency, yield, and environmental control (Jerca *et al*., 2024) [21]. Hydroponic and aeroponic systems use 70–95% less water, while aquaponics can reduce fertilizer dependence by up to 80% (Goddek *et al*., 2019) [16]. Lettuce grown in these systems has been shown to exhibit 20–30% higher vitamin C concentrations (Buchanan & Omaye, 2013) [9], improved crispness, and more consistent morphology. Furthermore, the ability to cultivate crops in urban or climate-inhospitable regions reduces supply chain vulnerabilities and enhances geographic flexibility. However, these benefits are tempered by significant initial capital costs—ranging from $50/m² for hydroponics to over $2000/m² for advanced vertical farms (Kozai *et al*., 2016) [23]-as well as high electricity consumption, often exceeding 5–10 kWh per kilogram of produce (Graamans *et al*., 2018) [18]. Moreover, these systems require skilled operation and continuous monitoring, presenting barriers to adoption in low-resource settings.

Despite these challenges, the future of unconventional lettuce cultivation is bright. Renewable energy integration—especially solar and wind—can mitigate environmental impacts, potentially reducing carbon footprints by 40–60% (Al-Chalabi, 2015) [1]. Advances in LED technology, now reaching efficiencies of 3.5 µmol/J (Philips, 2023) [34], continue to lower lighting costs, while AI-driven control systems are optimizing nutrient scheduling and microclimate regulation, boosting yield and quality by up to 20% (Kozai *et al*., 2020) [24]. Circular economy innovations, such as repurposing food waste for nutrient generation in aquaponics, further enhance sustainability. Scaling these systems to suit local conditions-be it rooftop greenhouses in urban centers or decentralized aquaponic modules in peri-urban zones-offers a tailored path forward.

Materials and Methods

Data Collection

A systematic literature review was conducted to gather data on lettuce cultivation in unconventional systems. Sources included peer-reviewed journals (PubMed, ScienceDirect, Frontiers, MDPI), conference proceedings, and reports from agricultural institutions, spanning 2018 to 2025. Search terms included "lettuce cultivation," "hydroponics," "aeroponics," "aquaponics," "vertical farming," and "controlled-environment agriculture." The initial search yielded 3,124 articles, reduced to 87 after applying inclusion criteria: studies focusing on lettuce, unconventional systems, and quantitative growth or quality metrics. Duplicates and non-peer-reviewed sources were excluded.

Data Presentation and Interpretation

Data were categorized by cultivation system, growth parameters (e.g., yield, fresh weight, leaf area), and environmental factors (e.g., nutrient delivery, lighting). Quantitative results were extracted and normalized (e.g., yield in kg m^{-2}) for comparison. Qualitative data, such as microbial safety and consumer perceptions, were synthesized narratively. Statistical tools (e.g., meta-analysis, ANOVA) from referenced studies were used to interpret heterogeneity and effect sizes. Tables were created using Python (Matplotlib) and MS Excel to visualize trends, such as yield comparisons and nutrient uptake. Sources were cited for all claims, ensuring traceability.

Result Derivation

Results were drawn by synthesizing findings across studies, correlating parameters like nutrient delivery (e.g., Ebb & Flow vs. NFT) with outcomes like yield and nutrient content. Comparative analyses ranked systems based on productivity, resource efficiency, and sustainability. The search was conducted via academic databases and validated through cross-referencing with Web of Science and Google Scholar.

Results

A meta-analysis of 87 studies reveals the transformative power of unconventional cultivation systems-hydroponics (NFT and DWC), aeroponics, aquaponics, and vertical farming-in revolutionizing lettuce production. These systems consistently surpass traditional soil-based methods, delivering higher yields, superior resource efficiency, and enhanced produce quality. Hydroponic systems achieve robust yields of 0.98–1.21 kg m^{-2} through precise nutrient delivery and optimized environmental controls, such as temperature, humidity, and CO_2 levels. Vertical farming redefines space-efficient agriculture with an exceptional yield of 6.88 kg m^{-2}, leveraging stacked cultivation. Aeroponics promotes remarkable root development, with root/shoot ratios 2–3 times higher than hydroponics, though shoot biomass is limited by nutrient misting dynamics. Aquaponics, utilizing fish waste as fertilizer, matches hydroponic yields but requires stringent microbial safety measures. Key performance drivers include nutrient delivery precision, advanced LED lighting, and environmental regulation, positioning these systems as vital solutions for global food security in resource-constrained settings.

Comparative Analysis of Cultivation Systems

Unconventional systems demonstrate distinct strengths and trade-offs in yield, resource use, and safety (Table 1). Hydroponics (NFT and DWC) delivers yields of 1.05–1.15 kg m^{-2}, with water use reduced by up to 90% compared to soil-based methods (260 L/kg). Vertical farming achieves the highest yield at 6.88 kg m^{-2} but demands significant energy (20 kWh/m²), highlighting the need for sustainable energy solutions. Aeroponics, with a yield of 0.95 kg m^{-2}, excels in water efficiency (15 L/kg) and root growth, making it ideal for space-limited urban environments. Aquaponics, yielding 1.00 kg m^{-2}, supports a closed-loop model but faces challenges with microbial risks, such as E. coli, requiring rigorous safety protocols. Soil-based systems, with the lowest yield (0.85 kg m^{-2}) and high water use, are increasingly outpaced by these innovative approaches.

Table 1: Comparative Analysis of unconventional cultivation systems, highlighting trade-offs in yield, resource use, and safety

System	Yield (kg m^{-2})	Water Use (L/kg)	Energy Use (kWh/m²)	Nutrient Source	Microbial Risk	Statistical Results	Reference
Hydro-NFT	1.05	20	10	Inorganic/Organic	Low	Yield (SD ±0.08): $p < 0.01$; Water consumption (SD ±2.5): $p < 0.001$; Energy use (SD ±1.2): $p < 0.01$.	Barbosa *et al*., 2023; Goddek *et al*., 2021
Hydro-DWC	1.15	25	12	Inorganic/Organic	Moderate	Yield (SD ±0.10): $p < 0.01$; Water consumption (SD ±3.0): $p < 0.001$; Energy use (SD ±1.5): $p < 0.01$	Barbosa *et al*., 2023; Goddek *et al*., 2021
Aeroponics	0.95	15	15	Inorganic	Low	Yield (SD ±0.07): $p < 0.05$; Water consumption (SD ±2.0): $p < 0.01$; Energy use (SD ±1.8): $p < 0.05$.	Petrea *et al*., 2022
Aquaponics	1.00	30	8	Fish Waste	High	Yield (SD ±0.09): $p < 0.05$; Water consumption (SD ±3.5): $p < 0.01$; Energy use (SD ±1.0): $p < 0.05$	Maucieri *et al*., 2020
Vertical	6.88	10	20	Inorganic/Organic	Low	Yield (SD ±0.35): $p < 0.001$; Water consumption (SD ±1.5): $p < 0.001$; Energy use (SD ±2.0): $p < 0.001$.	Sharath Kumar *et al*., 2023
Soil-Based	0.85	260	5	Soil/Fertilizer	High	Yield (SD ±0.06): $p < 0.01$; Water consumption (SD ±20): $p < 0.001$; Energy use (SD ±0.8): $p < 0.01$.	Barbosa *et al*., 2023; Sharath Kumar *et al*., 2023

Nutrient Uptake in Unconventional Systems

Nutrient uptake varies significantly across systems (Table 2). Hydroponics shows moderate nitrogen uptake (2.13%) with lower levels of phosphorus, potassium, calcium, and magnesium. Aeroponics achieves higher nitrogen uptake (3.29%) and enhanced macro-nutrient absorption, supporting robust root systems. Aquaponics records substantial nutrient uptake (~5.96 g/head), comparable to hydroponics, while vertical farming mirrors hydroponic nutrient profiles, yielding plants with fresh weights of 15–17 g. Soil-based systems, enhanced by organic amendments, exhibit superior chlorophyll, carotenoid, and nutrient content (N, P, K), but their inefficiencies limit scalability.

Table 2: Overview of nutrient uptake by lettuce in unconventional systems.

System	N Uptake	Other Nutrients
Hydroponic	2.13%	Lower P, K, Ca, Mg
Aeroponic	3.29%	Higher macro uptake
Aquaponic	~5.96 g/head	Comparable composition
Vertical	Similar to hydroponics	Similar fresh weight ~15–17 g/plant
Soil-Based	Enhanced with organic amendments	Better chlorophyll, carotenoids, leaf N, P, K

Specific Results and Contemporary Significance

Each system addresses unique agricultural challenges with profound implications for sustainability. Hydroponics, including Nutrient Film Technique (NFT) and Deep-Water Culture (DWC), typically yields between 1.05 and 1.15 kg per square meter. While organic fertilizers in these systems enhance phenolic content and improve nutritional quality, biomass production is slightly lower compared to inorganic solutions. Nonetheless, hydroponics' drastic reduction in water usage renders it invaluable for water-scarce urban agriculture. Aeroponics, on the other hand, excels in promoting root development—often twice that observed in hydroponics—while using minimal water. This makes it particularly suited for cultivating high-value crops in compactmeter.

Aquaponics integrates hydroponic plant cultivation with aquaculture, producing yields comparable to hydroponics (approximately 1.00 kg per square meter) while embodying circular economy principles through the recycling of fish waste as nutrients. However, to ensure the system's scalability, it must overcome microbial contamination risks with advanced food safety measures. Vertical farming stands out for its extraordinary productivity, achieving up to 6.88 kg per square meter through stacked layers and LED lighting. This makes it a critical solution for urban food security, though its high energy requirements necessitate the incorporation of renewable energy sources to ensure environmental sustainability.

Consumer perception also plays a significant role in the adoption of these systems. Research, including studies involving Spanish consumers, reveals a general preference for local and small-scale agricultural practices over vertical farming, despite the latter demonstrating a 44% reduction in CO_2 emissions compared to traditional methods. Bridging this perception gap through educational initiatives is vital to facilitate broader public acceptance and integration of advanced agricultural technologies. These findings are critical in an era of rapid urbanization, climate volatility, and supply chain disruptions. Unconventional systems enable food production in unconventional spaces—deserts, rooftops, and repurposed buildings—ensuring resilience and sustainability. Their ability to enhance produce quality, such as higher antioxidants in organic hydroponics, meets rising consumer demand for nutritious, safe, and eco-friendly food.

Comparison and Ranking

Vertical farming leads with the highest yield of 6.88 kg m^{-2}, making it an ideal solution for land-scarce urban environments. However, its high energy requirements call for the integration of sustainable innovations to enhance efficiency. Hydroponics, particularly the Deep-Water Culture (DWC) method, offers a respectable yield of 1.15 kg m^{-2}. It is valued for its water efficiency and flexible nutrient management, making it adaptable to a wide range of agricultural settings (Fig 1). The Nutrient Film Technique (NFT) variant of hydroponics delivers a slightly lower yield of 1.05 kg m^{-2} but stands out due to its simpler infrastructure, making it well-suited for small-scale urban farms. Aquaponics matches hydroponic yields at around 1.00 kg m^{-2} and promotes sustainability by integrating fish farming, though the potential for microbial contamination presents challenges for scalability unless strong safety measures are in place. Aeroponics, yielding 0.95 kg m^{-2}, excels in promoting root growth and conserving water, rendering it ideal for niche, high-value crop production. Traditional soil-based cultivation lags behind with the lowest yield of 0.85 kg m^{-2}, coupled with high water usage and vulnerability to soil-borne diseases, highlighting the limitations of conventional farming practices.

Fig 1: Different unconventional methods of cultivation are being adopted in contemporary agriculture, revolutionizing food production. These include an innovative vertical farm, blending cutting-edge hydroponic systems like DEC and NFT, alongside aquaponics and aeroponics, alongside traditional soil-based techniques

Discussion

Unconventional cultivation systems—hydroponics (NFT and DWC), aeroponics, aquaponics, and vertical farming-redefine sustainable lettuce production by optimizing resource efficiency and enhancing yield and quality in controlled environments. These systems enable cultivation in non-traditional spaces like urban rooftops and deserts, addressing global challenges such as land scarcity and climate variability, with urban populations expected to reach 68% by 2050 (United Nations, 2018) [44]. Their ability to reduce water use by up to 90% compared to soil-based methods makes them vital for water-scarce regions, but challenges like energy demands and microbial risks require further innovation to ensure scalability and consumer acceptance (Stoica *et al*., 2022) [41].

The biological foundation of these systems lies in their precise control over nutrient uptake and plant metabolism. Hydroponics and vertical farming deliver nutrients directly to roots, achieving nitrogen uptake rates of 2.13–3.29%, significantly higher than soil-based systems where nutrient leaching reduces efficiency (Sardare & Admane, 2013) [37]. Aeroponics enhances root growth, with root/shoot ratios 2-3 times higher than hydroponics, driven by oxygen-rich environments that boost aerobic respiration and auxin signaling (Hayden, 2006) [19]. However, its lower shoot biomass suggests a need to optimize nutrient misting to balance carbon allocation (Britto & Kronzucker, 2002) [8]. Aquaponics, reliant on microbial nitrogen cycling from fish waste, matches hydroponic yields but demands rigorous microbial management to prevent nutrient variability and pathogen risks (Wongkiew *et al*., 2017) [47]. These nutrient dynamics directly influence photosynthetic efficiency, as controlled systems enhance carbon fixation and secondary metabolite production.

Photosynthetic performance in unconventional systems is amplified by tailored LED lighting, which optimizes photosystem II activity and boosts yields, particularly in vertical farming (6.88 kg m^{-2}) (Kozai *et al*., 2016) [23]. Studies on greenhouse tomato cultivation highlight the role of controlled climatic factors, such as temperature and CO_2, in enhancing photosynthesis and biochemical attributes like antioxidant content, which are similarly leveraged in hydroponics and vertical farming (Arshad *et al*., 2023a) [4]. Organic fertilizers in hydroponics further increase phenolic content by activating the phenylpropanoid pathway, meeting consumer demand for nutrient-dense produce (Suriani *et al*., 2021, MICU *et al*., 2024) [42, 29]. Soil-based systems, limited by variable natural light, often yield lower photosynthetic rates. Additionally, precise environmental control in these systems minimizes abiotic stress, reducing reactive oxygen species and enhancing plant resilience (Gill & Tuteja, 2010) [15], which is critical for consistent growth and quality.

System-specific advantages reveal their potential for sustainable agriculture. Hydroponics achieves yields of 1.05–1.15 kg m^{-2} with high water efficiency, but DWC systems require monitoring to mitigate microbial risks that could trigger defense responses and reduce growth (Dangl & Jones, 2001) [11]. Research on NFT systems for leafy vegetables like amaranth and basella demonstrates that optimized nutrient delivery enhances growth rates and biochemical quality, supporting hydroponics' suitability for diverse crops (Chan *et al*., 2023) [10]. Aeroponics excels in water efficiency (15 L/kg) but needs refined misting protocols to improve shoot yields. Aquaponics' closed-loop system aligns with sustainability goals, yet microbial contamination risks necessitate advanced filtration (Wongkiew *et al*., 2017) [47]. Vertical farming's high yields are energy-intensive, requiring renewable energy integration to reduce its carbon footprint (Sharma *et al*., 2020) [38]. Consumer preferences favoring local agriculture over vertical farming, despite its lower emissions, underscore the need for education to align perceptions with sustainability benefits (Sharma *et al*., 2020) [38].

Challenges in these systems highlight areas for future research. Aeroponics' shoot biomass limitations call for studies on nutrient delivery optimization. Aquaponics requires probiotic interventions to stabilize microbial communities, while vertical farming needs energy-efficient solutions (Wongkiew *et al*., 2017; Sharma *et al*., 2020) [47, 38]. Research on biochar's role in mitigating abiotic stress in plants suggests potential applications in hydroponics and aquaponics to enhance nutrient retention and stress tolerance (Ali *et al*., 2024) [2]. The long-term impact of controlled environments on plant genetic diversity also warrants investigation to ensure adaptability to external stresses (Gill & Tuteja, 2010) [15]. By addressing these biological and practical hurdles, unconventional systems can bridge the gap between scientific innovation and societal needs for sustainable food production.

Conclusion

Unconventional lettuce cultivation systems—hydroponics, aeroponics, aquaponics, and vertical farming—represent a paradigm shift in agriculture, addressing global challenges like land scarcity, water shortages, and urbanization. Vertical farming leads in yield, while hydroponics offers a balance of productivity and efficiency. Aquaponics and aeroponics, though innovative, face hurdles in scalability and nutrient delivery. These systems collectively reduce environmental impacts, enhance food quality, and enable production in unconventional spaces, aligning with sustainable development goals. The way forward involves leveraging AI, renewable energy, and cultivar-specific research to optimize these systems. Future studies should focus on reducing energy costs, improving microbial safety in aquaponics, and developing affordable solutions for smallholder farmers, ensuring equitable access to these transformative technologies.

References

1. Al-Chalabi M. Vertical farming: Skyscraper sustainability? Sustainable Cities and Society. 2015; 18:74-77.
2. Ali B, Arshad A, Javed MA, Kaplan A, Suleman F, Hafeez A, *et al*. Biochar-induced regulation on primary and secondary metabolites in plants under abiotic stress. Biochar in Mitigating Abiotic Stress in Plants. 2024, 119-133.
3. Arshad A, Cîmpeanu SM, Jerca IO, Sovorn C, Ali B, Badulescu LA, Drăghici EM. Assessing the growth, yield, and biochemical composition of greenhouse cherry tomatoes with special emphasis on the progressive growth report. BMC Plant Biology. 2024; 24(1):1002.
4. Arshad A, Sovorn C, Draghici EM, Jerca IO, Iqbal N. Study on the influence of climatic factors in greenhouses on the growth, yield and biochemical attributes of tomatoes grown in the soilless system during the summer season. Modern Concepts & Developments in Agronomy. 2023a; 14(2):1350-1358.
5. Barbosa GL, *et al*. Comparison of land, water and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. International Journal of Environmental Research and Public Health. 2015; 12(6):6879-6891.
6. Barbosa GL, Gadelha FDA, Kublik N, Proctor A, Reichelm L, Weissinger E, *et al*. Let-Us Investigate; A Meta-Analysis of Influencing Factors on Lettuce Crop Yields within Controlled-Environment Agriculture Systems. Frontiers in Plant Science. 2023; 14:1043571. Doi: https://doi.org/10.3389/fpls.2023.1043571
7. Beacham AM, *et al*. Vertical farming: A future perspective for sustainable agriculture. Trends in Food Science & Technology. 2019; 91:416-421.
8. Britto DT, Kronzucker HJ. NH4+ toxicity in higher plants: A critical review. Journal of Plant Physiology. 2002; 159(6):567-584. Doi: https://doi.org/10.1078/0176-1617-0774
9. Buchanan DN, Omaye ST. Comparative study of ascorbic acid and tocopherol concentrations in hydroponic and soil-grown lettuces. Food and Nutrition Sciences. 2013; 4(10):1047-1053.
10. Chan S, Jerca IO, Arshad A, Drăghici EM. Preliminary study on two leafy vegetables grown in different growing conditions in NFT system (Amaranthus viridis L and Basella rubra L). Scientific Papers. Series B. Horticulture. 2023; 67(1).
11. Dangl JL, Jones JDG. Plant pathogens and integrated defence responses to infection. Nature. 2001; 411(6839):826-833. Doi: https://doi.org/10.1038/35081161

12. Despommier D. The Vertical Farm: Feeding the World in the 21st Century. Macmillan, 2010.
13. FAO. Faostat: Crops and livestock products. Food and Agriculture Organization of the United Nations, 2023.
14. Farran I, Mingo-Castel AM. Aeroponic techniques for lettuce production. Acta Horticulturae. 2006; 719:297-302.
15. Gill SS, Tuteja N. Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. Plant Physiology and Biochemistry. 2010; 48(12):909-930. Doi: https://doi.org/10.1016/j.plaphy.2010.08.016
16. Goddek S, *et al*. Aquaponics and global food challenges. In Aquaponics Food Production Systems. Springer. 2019, 3-17.
17. Goddek S, Joyce A, Kotzen B, Burnell GM. Evaluation of Hydroponic Systems for Organic Lettuce Production in Controlled Environment. Frontiers in Sustainable Food Systems. 2021; 5:673231. Doi: https://doi.org/10.3389/fsufs.2021.673231
18. Graamans L, *et al*. Plant factories versus greenhouses: Comparison of resource use efficiency. Agricultural Systems. 2018; 160:31-43.
19. Hayden AL. Aeroponic and hydroponic systems for medicinal herb production. HortTechnology. 2006; 16(2):234-242. Doi: https://doi.org/10.21273/HORTTECH.16.2.234
20. Jensen MH, Malter AJ. Protected agriculture: A global review. World Bank Technical Paper. 1995; 253.
21. Jerca IO, Cîmpeanu SM, Teodorescu RI, Drăghici EM, Nițu OA, Sannan S, *et al*. A Comprehensive Assessment of the Morphological Development of Inflorescence, yield potential and growth attributes of Summer-Grown, Greenhouse Cherry tomatoes. Agronomy. 2024; 14(3):556.
22. Jones JB. Hydroponics: A Practical Guide for the Soilless Grower. CRC Press, 2016.
23. Kozai T, *et al*. Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production. Academic Press, 2016..
24. Kozai T, *et al*. Advances in plant factory technologies. Frontiers in Plant Science. 2020; 11:614.
25. Kratky BA. A suspended pot, non-circulating hydroponic method. Acta Horticulturae. 2010; 841:297-300.
26. Lakhiar IA, *et al*. Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. Journal of Plant Interactions. 2018; 13(1):338-352.
27. López-Gálvez F, Gil MI, Allende A. How Do Spanish Consumers Perceive Different Lettuce Cultivation Systems? Food Quality and Preference. 2024; 112:105023. Doi: https://doi.org/10.1016/j.foodqual.2024.105023
28. Maucieri C, Nicoletto C, van Os E, Anseeuw D, Van Havermaet R, Junge R. Evaluation of Lettuce Production under Hydroponic System: Nutrient Solution Derived from Fish Waste vs. Inorganic Nutrient Solution. Agronomy. 2020; 10(9):1254. Doi: https://doi.org/10.3390/agronomy10091254
29. Micu Daniela (Balint), Elena Dobrin, Ovidiu Ionuț Jerca, Elena Maria Drăghici. Study on the effect of nutrient concentration on quality parameters for lettuce grown on various substrate types, Scientific Papers. Series B, Horticulture. 2024; 68(2):479-485. P ISSN 2285-5653, CD-ROM ISSN 2285-5661, E ISSN 2286-1580
30. NASA. Plant growth facility: Growing plants in space. National Aeronautics and Space Administration, 2021.
31. Nitu OA, Ivan EŞ, Tronac AS, Arshad A. Optimizing Lettuce Growth in Nutrient Film technique hydroponics: Evaluating the impact of elevated oxygen concentrations in the Root Zone under LED illumination. Agronomy. 2024; 14(9):1896.
32. Nitu OA, Ivan EŞ, Tronac AS, Arshad A. Variety-Specific Lettuce Responses to Oxygen-Enriched Water and LED Light in a Controlled Greenhouse: A Multivariate Analysis Across Two Cycles. International Journal of Plant Biology. 2025; 16(1):29.
33. Petrea SM, Simionov IA, Antache A, Popa M, Ionescu V, Cristea V. Growth Responses and Root Characteristics of Lettuce Grown in Aeroponics, Hydroronics and Substrate Culture. Agriculture. 2022; 12(8):1106. Doi: https://doi.org/10.3390/agriculture12081106
34. Philips. LED grow lights: Technical specifications. Signify, 2023.
35. Rakocy JE, *et al*. Aquaponic production of tilapia and lettuce: System design and yields. Acta Horticulturae. 2006; 742:231-238.
36. Resh HM. Hydroponic Food Production: A Definitive Guidebook. CRC Press, 2022.
37. Sardare MD, Admane SV. A review on plant without soil-hydroponics. International Journal of Research in Engineering and Technology. 2013; 2(3):299-304.
38. Sharma N, Acharya S, Kumar K, Singh N, Chaurasia OP. Hydroponics as an advanced technique for vegetable production: A review. International Journal of Current Microbiology and Applied Sciences. 2020; 9(5):2354-2362. Doi: https://doi.org/10.20546/ijcmas.2020.905.268
39. Sharath Kumar M, Heuvelink E, Marcelis LFM. Environmental Implications of Lettuce Sourcing: Comparison of Sourcing from Vertical Farms and Conventional Production. Journal of Cleaner Production. 2023; 389:135987. Doi: https://doi.org/10.1016/j.jclepro.2023.135987
40. Specht K, *et al*. Urban agriculture of the future: An overview of sustainability aspects of food production in and on buildings. Agriculture and Human Values. 2016; 33(2):477-494.
41. Stoica Claudia Maria, Velcea Marian, Chira Lenuța, Jerca Ovidiu Ionuț, Velea Marius Alexandru, Drăghici Elena Maria. The nutrient solution oxygenation influence on the growth of the species lactuca sativa l. Root system cultivated in the nutrient film technique (NFT) system, Scientific Papers. Series B, Horticulture. 2022; 66(1):533-540. P ISSN 2285-5653, CD-ROM ISSN 2285-5661, E ISSN 2286-1580, http://horticulturejournal.usamv.ro/pdf/2022/issue_1/Art79.pdf
42. Suriani NL, Lee WJ, Ashari M. Nutrient management in hydroponics: A review on the enhancement of secondary metabolites in vegetables. Acta Horticulturae. 2021;1321:131-138.
43. UNCCD. Global land outlook 2022. United Nations Convention to Combat Desertification, 2022.
44. United Nations. World urbanization prospects: The

2018 revision. United Nations Department of Economic and Social Affairs, 2018.

45. USDA. Urban agriculture and innovative production grants. United States Department of Agriculture, 2024.
46. Wong CE, Teo ZWN, Shen L. Evaluation of Growth Responses of Lettuce and Energy Efficiency of the Substrate and Smart Hydroponics Cropping System. Horticulturae. 2021; 7(11):463. Doi: https://doi.org/10.3390/horticulturae7110463
47. Wongkiew S, Hu Z, Chandran K, Lee JW, Khanal SK. Nitrogen transformations in aquaponic systems: A review. Aquacultural Engineering. 2017; 76:9-19. Doi: https://doi.org/10.1016/j.aquaeng.2017.01.004